Faculty of Agriculture and Forestry
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COST-EFFICIENT NUTRIENT LOAD REDUCTION IN WASTEWATER TREATMENT PLANTS

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Doctoral dissertation

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ABSTRACT

The main theme in this dissertation is to determine the means of achieving the Baltic Sea Action Plan targets, with an emphasis on municipal wastewaters. Thus, the nitrogen and phosphorus reduction potentials of wastewater treatment plants and costs of nutrient reductions are calculated. The nutrient reduction potential is huge for municipal wastewater. Furthermore, abating nutrients in wastewater treatment plants is cheaper than previously thought. In particular, phosphorus abatement costs are much lower than those in agriculture. A numerical model is built to demonstrate that a considerable share of the targets of the Baltic Sea Action Plan can be met by nutrient abatement in wastewater treatment plants. Moreover, it is shown that with properly designed initial allocations, a nutrient trading scheme can even out the cost burden between wastewater treatment plants. However, transaction costs may play a significant role in nutrient trading in the Baltic Sea region. With an analytical model, it is demonstrated that if a water utility has market power, a tightening nutrient policy may decrease the price of potable water but increase the wastewater tariff. Based on the analytical model, a numerical model is built to illustrate that households connected to small water utilities face higher prices and higher price increases associated with environmental protection measures than do households connected to large water utilities. Finally, it is shown when the level of nutrient abatement reaches the upper limit, the costs water utilities face no longer depend on the instrument applied.

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

I Hautakangas S, Ollikainen M, Aarnos K, Rantanen P (2014) Nutrient abatement potential and abatement costs of waste water treatment plants in the Baltic Sea region. *Ambio* 43:352-360.

II Hautakangas S, Ollikainen, M (2019) Nutrient trading between wastewater treatment plants in the Baltic Sea region. *Environmental and Resource Economics* 73:533-556.

III Hautakangas S, Ollikainen M (2020) Impacts of alternative nutrient abatement policies on utilities supplying water and abating nutrients. Submitted.

The publications are referred to in the text by their roman numerals.

ABBREVIATIONS

AC	average cost
BAT	best available technology
BSAP	Baltic Sea Action Plan
GDP	gross domestic product
HELCOM	The Baltic Marine Environment Protection Commission
LWU	large water utility
MAC	marginal abatement cost
MC	marginal cost
MR	marginal revenue
NEFCO	The Nordic Environment Finance Corporation
NTS	nutrient trading scheme
PE	person equivalent
SWU	small water utility
TAC	total abatement cost
UWWTD	Urban Wastewater Treatment Directive
WQT	water quality trading
WWTP	wastewater treatment plant

1 INTRODUCTION

1.1 EUTROPHICATION AS AN ECONOMIC PROBLEM

Eutrophication is a common problem in water systems across the world. The term eutrophication refers to an increase in the rate of supply of organic matter to an ecosystem (Nixon 1995). This process leads to increased primary production and the growth of plants and causes plenty of changes in ecosystems (EEA 2001). Eutrophication has serious consequences for the marine environment, including declines in water transparency, increases in algal blooms, the loss of benthic vegetation and hypoxia among others (Nixon 1995). Through these changes, the usability of waters is affected, for example, fishing and recreational use. Hence, eutrophication influences the economy by, for example, changing a fishery or nature tourism facilities.

Inputs of nitrogen and phosphorus to coastal environments have stimulated the autochthonous production of organic material by aquatic primary producers (Nixon 1995). Although these nutrients are the restrictive factors for the growth of the plants in most cases, the interaction between nitrogen and phosphorus in water systems is a complicated issue (EEA 2001). There are nutrients in water systems from natural sources, and ecosystems need them to function. In addition to the internal nutrient cycle within a water system, the system also receives external loads from, for example, forests and air. However, external natural loads are not the main issue associated with eutrophication, whereas anthropogenic loading is.

Human activity produces nutrient loads of several kinds in the Baltic Sea region. There are nonpoint (diffuse) sources of nutrients such as agriculture and forestry and point sources such as industrial plants and wastewater treatment plants (WWTPs). Nonpoint sources cannot be monitored on a continuous and widespread basis with reasonable accuracy or at reasonable cost, while point source loads can often be measured at a single spot (Shortle and Dunn 1986). Moreover, nonpoint pollution is inherently stochastic (Shortle and Dunn 1986).

The Baltic Sea is a shallow semi-closed sea with brackish water that is partially ice-covered every winter. In addition, ca. 90 million people live in the catchment area. Thus, anthropogenic nutrient loads in the past and today have severely influenced marine ecosystems. Eutrophication is a well-acknowledged problem in the Baltic Sea, and it is most visible during blue algae blooms in the summer. Combating eutrophication requires large reductions in nutrient loads (HELCOM 2007). The two main sources of external nutrient loads in the Baltic Sea are agriculture and municipal wastewater. According to The Baltic Marine Environment Protection Commission (Helsinki Commission or HELCOM), of the nitrogen load, agriculture accounts for 50%, and municipal wastewaters accounts for 25%.

For the phosphorus load, agriculture accounts for 35%, and municipal wastewaters accounts for 50% of the aggregate load (HELCOM 2009).

HELCOM launched the Baltic Sea Action Plan (BSAP) in 2007 and updated it in 2013 (HELCOM 2007; 2013). The target of the BSAP is the good ecological status in the Baltic Sea. Concerning eutrophication and nutrients, clear water with transparency as an indicator is a primary ecological objective (HELCOM 2007). HELCOM (2013) has set nutrient reduction targets for countries. The overall annual reduction targets for the Baltic Sea littoral countries compared with those in the reference years 1997-2003 are 89,260 tons of nitrogen and 14,374 tons of phosphorus. The reference annual inputs are 910,344 tons of nitrogen and 36,894 tons of phosphorus. For WWTPs, HELCOM recommends abating 70% of nitrogen and 90% of phosphorus (HELCOM 2007). Additionally, the requirements of the EU's Urban Wastewater Treatment Directive (UWWTD) are 70% abatement of nitrogen and 80% abatement of phosphorus in all WWTPs larger than 10,000 PE[1] in the catchment area of the Baltic Sea (EEC 1991).

People generate wastewater in their everyday life by doing laundry, washing dishes, using the bathroom, etc. Wastewater contains different kinds of substances detrimental to ecosystems. In rural areas, wastewater is usually disposed of at the households level, but in densely populated areas such as urban areas, wastewater is often treated by WWTPs. These plants remove harmful substances from the wastewater before being released into the water system. One of the main tasks WWTPs perform is nutrient abatement, by which nitrogen and phosphorus are removed from the effluent water.

When a WWTP is designed to abate BOD (biological oxygen demand) and COD (chemical oxygen demand), it also abates nitrogen and phosphorus from the sewage waters at approximately the 30% level with mechanical treatment. More ambitious levels of abatement need more advanced technologies. If the target is to abate 50% of nitrogen and 70% of phosphorus, WWTPs need to employ combined mechanical-biological treatment technology. Adding chemical treatments to the repertoire can abate nitrogen at the 85% level and phosphorus at the 98% level. With advanced technologies, even higher reduction rates are possible. In practice, the highest average abatement levels in the long term are approximately 95% for nitrogen and approximately 98% for phosphorus. (Hautakangas et al. 2014; EC 2017).

Often, WWTPs operate with a potable water supply unit within a water utility. This interconnection means that an environmental policy aimed at reducing nutrient loads affects the whole water utility and thus the households connected to it. Even the choice of a policy instrument may affect water prices. From the household perspective, the size of the water utility they are connected to may affect the impact they encounter from environmental policy.

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[1] 1 PE (person equivalent) = 70 g/day of BOD7 (the organic biodegradable load having a 7-day biochemical oxygen demand of oxygen per day; calculated on the basis of the maximum average weekly load per day entering the WWTP, excluding unusual situations (FINLEX (2006))

Negative externalities, such as emissions, can be internalized by authority interventions by using environmental policy instruments. These instruments can be divided into two categories: economic market-based instruments and command-and-control instruments, i.e., direct regulation approaches. Economic instruments include, for example, emission taxes, subsidies and marketable permits, while quantity constraint is one of the command-and-control approaches. (Xepapadeas 1997).

Under quantity constraints, authorities set a physical limit to the amount of a substance emitted or to some level of required abatement. Either the same quantity constraint is set for all polluters involved or several different quantity constraints are specifically tailored. This approach seldom leads to a cost-effective solution. The Pigouvian environmental tax, on the other hand, is cost-effective. Authorities levy a tax on an emitted unit and provide an incentive to polluters to reduce emissions to the point where the marginal cost of the emission reduction for the polluter equals the tax rate ($t = MAC$ (marginal abatement cost)). Now, it is not profitable to emit less because reducing emissions one more unit is more expensive than paying a tax on that unit. Nor it is not profitable to emit more because by emitting one more unit, the polluter must pay a tax on that unit, which is higher than the cost of abating that unit. Imposing a tax on emissions at a level that both results in needed emission reductions and equalizes the MACs of the polluters minimizes the costs of achieving the target, as shown by Baumol and Oates (1971). If the regulator does not know the correct MAC functions, the tax rate may be set too low or too high. In the first case, the level of emissions will be higher than society wants, and in the second case, it will be lower. By adjusting the tax rate, the correct one will be identified, but this may cause inappropriate costs and investments for polluters (Hanley et al. 1997).

The idea of marketable pollution permits originated from Crocker (1966) and Dales (1968). The main idea of marketable pollution permits is to define property rights for environmental resources and make them tradeable. There are several ways to carry out emissions trading, but in general, there is a certain level of emissions that society wants to reach. The allowances for emissions are then allocated with some principle for the polluters, after which they can trade the allowances. Irrespective of the initial allocation scheme, perfect markets will achieve equilibrium, where the trading of allowances yields a cost-efficient solution (Montgomery 1972). The price of the allowances reflects the costs of reducing emissions. All sources face the same price. A solution will be obtained at the point where the marginal cost of an emission reduction equals the allowance price ($\mu = MAC$). Now, it is not profitable to emit less because reducing emissions one more unit is more expensive than what the polluter gets by selling an allowance for that unit. Nor it is not profitable to emit more because by emitting one more unit, the polluter needs to buy one more allowance with a price higher than the cost of abating that unit. With uniformly mixed pollutants, the equality of MACs can be achieved among the polluters at that level. Marketable permits have the advantage of quantity constraints in that the regulator knows the total emission level and the advantage of the Pigouvian tax, i.e., cost-effectiveness. In practice, there are several issues we must assess before launching an emissions trading scheme: 1. the quantity of permits; 2. implementing a cap-and-trade or baseline-and-credit approach; 3. providing permanent or temporary permits; 4. grandfathering or auctioning allocations; 5. determining a trading ratio and the parties within the market; and 6. administration and monitoring.

Previous work on nutrient abatement costs in WWTPs is limited. HELCOM and the Nordic Environment Finance Corporation (NEFCO) have analyzed abatement costs at current abatement levels in the Baltic Sea littoral countries (COWI 2007). Gren (2008b) studied the marginal costs of nitrogen and phosphorus abatement in WWTPs, and Hasler et al. (2012) concentrated on average abatement costs in the Baltic Sea littoral countries. Other studies of nutrient abatement costs include those by Bode and Lemmel (2001), Tsagarakis et al. (2003), Friedler and Pisanty (2006) and Berbeka et al. (2012).

There are numerous studies concerning emissions trading and active trading programs focused on greenhouse gases and air pollutants. Studies of nutrient trading, let alone nutrient trading programs, are relatively limited. Lankoski et al. (2008) studied nitrogen trading between point and nonpoint sources in the Kymi River basin in Finland. Elofsson (2010) analyzed nutrient trading to meet the BSAP targets, and Gren and Elofsson (2013) studied market power in nutrient trading markets. Other studies of nutrient trading include those by Ahlvik and Pavlova (2013) and Doyle et al. (2014). Most of the operating nutrient trading schemes (NTS) are in the USA. Since the 1990s, over 25 programs have been launched in the USA, with some 100 facilities participating (EPA 2008). The only program under which improvements in water quality have appeared is the Long Island Sound trading program (ENVTN 2014).

In the literature, there are only a few studies concerning the costs of water utilities as combined WWTP and potable water supply units; these include those by Renzetti (1999) and Renzetti and Kushner (2004). However, the environmental policy aspect was not incorporated into these studies.

1.2 OBJECTIVES

First, the objective of this dissertation is to assess nitrogen and phosphorus abatement costs and build abatement cost functions for WWTPs. The task also requires the determination of nitrogen and phosphorus loads from WWTPs and the abatement levels in WWTPs in the Baltic Sea littoral countries. With this information, the physical potential of reducing nutrients in WWTPs is calculated. These tasks are addressed in Article I with data gathered on WWTPs across the Baltic Sea littoral countries. These data reveal the current nutrient loads of WWTPs as well as their nutrient abatement levels. Using the detailed cost data on representative WWTPs, total abatement cost (TAC) functions and MAC functions are built for four size classes of WWTPs. The aggregate and country-wise costs of reducing nutrient loads are derived by combining the physical reduction potentials of WWTPs and the abatement cost functions. The work in Article I differs from that in the previous studies referred to in the previous section in that here, the nutrient abatement costs are based on detailed data related to the physical and financial operations of WWTPs.

Building on this information, the second objective is to find a cost-effective solution for reducing nitrogen and phosphorus loads in the WWTPs in the Baltic Sea littoral countries. Furthermore, how the costs are divided between the WWTPs, and how the initial allocation of allowances impacts market equilibrium and costs. The focus is on a cost-effective nutrient reduction in WWTPs not on the impact of the nutrients in the basins of the Baltic Sea. These aspects are explored in Article II by building a numerical nutrient trading model for the WWTPs in the Baltic Sea littoral countries. The initial allocations of allowances studied involve auctioning and grandfathering. The equilibrium solutions and costs faced by WWTPs are studied when trading nitrogen and phosphorus separately and when trading nitrogen equivalents. Moreover, the impact of transaction costs is also considered. Article II differs from the bulk of the water quality trading (WQT) literature in that it focuses on international nutrient trading in a sea area; it also focuses on many practical issues associated with nutrient trading and takes advantage of the nutrient abatement costs in WWTPs assessed with detailed data.

The third objective is to determine how nutrient tax and quantity constraint aimed at improving water quality impact the behavior of water utilities and thus households. This subject is the focus of Article III, which is based on an analytical model of a water utility that both supplies potable water and treats wastewater and a numerical model of two representative water utilities. The MACs built in Article I are also used in Article III for the numerical model along with data on the activity of two water utilities. The tightening of nutrient policies is studied with analytical and numerical models to determine how water rates and nutrient abatements are affected. This approach is executed under two different policy instruments: a nutrient tax and quantity constraint. The work in Article III differs from that in previous studies in that the impacts of an environmental policy on the costs and pricing behavior of a water utility and thus on households have not been scrutinized before.

This dissertation focuses on nitrogen and phosphorus reductions in WWTPs in the Baltic Sea region for four reasons. First, WWTPs are a significant source of nutrient loads in the Baltic Sea. Second, WWTPs are point sources that are easier to monitor than nonpoint sources. Third, the technologies developed for nutrient abatement in WWTPs enable high nutrient reduction levels. Fourth, the costs of the nutrient abatement process can be estimated using detailed data.

2 MATERIALS AND METHODS

To address the objectives of this work, the data on WWTPs across the Baltic Sea littoral countries were collected. There are hundreds of WWTPs across the Baltic Sea, and their sizes and performances vary greatly. The data are for WWTPs of at least 10,000 PE, as the EU and HELCOM requirements involve these plants in particular. Two main databases were used, namely, the EU and HELCOM databases, which were supplemented with data on large Russian WWTPs. The total number of WWTPs was 761, but reliable data were not available for all of them. The sample consisted of 182 WWTPs that were classified into four size classes[2]. A random sample was used for the WWTPs in Denmark, Finland, Germany, Russia and Sweden, but for the rest of the countries, the data used were those available. The sample was then generalized to correspond to all WWTPs country-wise. The sample concerning Denmark, Finland, Germany, Russia and Sweden was considered representative. For the WWTPs in Estonia, Latvia, Lithuania and Poland, the data were considered to have a self-selection bias, i.e. WWTPs were the most advanced. Thus, the estimated WWTPs with poor performance were added to the sample to reach the target number of WWTPs. Finally, the estimated amount of untreated wastewater in Russia and Poland was included. The main information used, in addition to the size of plants, included the nitrogen and phosphorus in the influents and effluents of WWTPs.

To assess the costs of reducing nutrients in WWTPs, abatement cost functions were built for nitrogen and phosphorus separately. As the abatement process of nitrogen and phosphorus in WWTPs is a joint process, one needs to separate the costs associated with nutrients. To execute this method, data on the investment and operative costs of selected WWTPs in the Baltic Sea region representing four different size classes were analyzed. The real interest rate used was 4%, and investments were assumed to have a 30-year-long life. Thus, the costs of nutrient abatement are annualized averages of the net present value. The abatement cost analysis for each nutrient was carried out by holding the other nutrient level constant. To form the functions describing abatement costs, the observed MAC/abatement points found in the data were fitted. The abatement cost function for each nutrient and size class is:

$$\mathrm{C}(q_{j_i}) = a_{j_i} + b_{j_i} q_{j_i} + c_{j_i} q_{j_i}^2, \qquad (1)$$

where $q_{j_i} > 0$ is the abatement of a nutrient in kg per year and j_i denotes the size class with $i = 1,2,3,4$ and $J = \{j_1, j_2, j_3, j_4\}$. Additionally, $a, b, c \in \mathbb{R}$ are constants, $C'(q_{j_i}) > 0$, and $C''(q_{j_i}) > 0$. Convexity in Eq. (1) holds

[2] 1: 10,000–80,000 PE, 2: 80,000–220,000 PE, 3: 220,000–500,000 PE, 4: >500,000 PE

automatically for positive constants $a, b,$ and c and for $c > |b|$ if $c > 0$ but $b < 0$ and abatement is sufficiently high.

The data on WWTPs are then used to analyze an NTS involving the WWTPs in the Baltic Sea littoral countries. A cost-efficient solution is obtained by allocating the abatements in the cheapest way to reach the predetermined level of total abatement in the Baltic Sea region. Following the recommendations by NEFCO (2008) and assuming that the NTS is designed for the Baltic Sea as a whole with a trading rule of 1:1, allows trading in a single market instead of multiple markets and trading ratios between sub-basins. In this model, the regulator sets a cap on loads, which corresponds to abating nitrogen at 90% and phosphorus at 95% aggregate levels. The best available technologies (BATs) used yield 95% and 98% abatement levels of nitrogen and phosphorus, respectively. The trading takes place between loads of the WWTPs measured at the end of the pipes.

The benchmark case with perfect information is based on cap-and-trade auctioning. First, the allowances, which allow us to load a total predetermined amount of nutrients in the Baltic Sea per year, are auctioned to the WWTPs. Another option used is grandfathering, where the allowances are distributed based on some criteria. This approach distributes the cost burden between WWTPs if the costs are unevenly divided. Two different grandfathering cases are analyzed, one of which is to distribute the allowances to the countries based on their inverse GDP per capita; thus, the higher the inverse GDP per capita is, the greater the allowance. In another grandfathering case, Poland is allocated 90% of the allowances.

The joint costs of all WWTPs in the size classes are minimized subject to the given abatement targets. Formally, a regulator solves the following problem over all plants in each size class:

$$\begin{aligned}\min_{\hat{q}_J} L = & \sum_{j_1=1}^{524}\left(a_{j_1} + b_{j_1}\hat{q}_{j_1} + c_{j_1}\hat{q}_{j_1}{}^2\right) + \sum_{j_2=1}^{158}\left(a_{j_2} + b_{j_2}\hat{q}_{j_2} + c_{j_2}\hat{q}_{j_2}{}^2\right) \\ & + \sum_{j_3=1}^{57}\left(a_{j_3} + b_{j_3}\hat{q}_{j_3} + c_{j_3}\hat{q}_{j_3}{}^2\right) + \sum_{j_4=1}^{19}\left(a_{j_4} + b_{j_4}\hat{q}_{j_4} + c_{j_4}\hat{q}_{j_4}{}^2\right) \\ & + \mu(\rho N - (\sum_{j=1}^{524}\hat{q}_{j_1} + \sum_{j=1}^{158}\hat{q}_{j_2} + \sum_{j=1}^{57}\hat{q}_{j_3} + \sum_{j=1}^{19}\hat{q}_{j_4})), \qquad (2)\end{aligned}$$

where μ is the Lagrangian multiplier, N refers to the total nitrogen inflows to the WWTPs across the region in kg, and ρ is the overall abatement target in percent. A similar problem applies to phosphorus by replacing N with P. The optimal solution entails all plants in each size class setting their MACs equal to the (endogenous) Lagrangian multiplier.

In the presence of nutrient trading, plants in any size class minimize the sum of abatement and emission allowance costs:

$$\min_{q_{j_i}}\left[\left(a_{j_i} + b_{j_i}q_{j_i} + c_{j_i}q_{j_i}^2\right) + p\left(u_{j_i} - q_{j_i} - x_{0j_i}\right)\right], \tag{3}$$

where p refers to the allowance price, u_J is the amount of incoming nutrient load to an installation j, and x_{0j} denotes the initial allowance of permits allocated to the installation. The optimal solution of the installation is obtained by setting the MAC equal to the allowance price. When authorities distribute allowances that are less than the actual loads before the allowance distribution takes place, the price of the allowance equals the value of the Lagrangian multiplier.

Nitrogen-equivalent trading based on the Redfield ratio is also studied. Then, the viewpoint is shifted from a perfectly functioning market to an NTS with transaction costs involved. In this case, the WWTPs in Poland are grandfathered with 90% of the allowances, and the remaining 10% are allocated to the remaining WWTPs. Only the sellers of the allowances face the transaction cost of 1 euro per kg.

Other policy instruments than nutrient trading explored in this dissertation are a nutrient tax and quantity constraint. The effects of these instruments on the operation of a water utility that both supplies potable water and treats wastewater are analyzed. An analytical model is developed for a representative water utility that supplies households with potable water and treats their wastewater. Moreover, it is assumed that the water utility has local market power and charges a two-part tariff with a fixed fee for the connection and water price divided into two components: a potable water price and a wastewater tariff. Both components are determined based on the use of potable water in households. The profit function of the unregulated water utility is:

$$\pi^0 = \hat{p}W(\hat{p}) - \phi(W(\hat{p})) + F(I) - c(q) - a(I), \tag{4}$$

where $\hat{p} = p + h(q)$ is the price of water, which is the sum of the price of potable water and the wastewater tariff. Additionally, $q = q_N + q_P$ refers to the sum of the abatement of nitrogen, N, and phosphorus, P. $W(\hat{p})$ is the household demand for water, and the cost of raw water is denoted by $\phi(W(\hat{p}))$. The fixed fee, $F(I)$, reflects the investments, I, of the water utility. Moreover, $c(q)$is the nutrient abatement cost, and $a(I)$ is the cost of sewers and pipelines.

The profit maximization problem of the water utility under nutrient tax, t_i, where $i = N, P$, (5a) and quantity constraint (5b) instruments is given by (assuming an interior solution):

$$\max_{p,q,I} \pi^t = \pi^0 - t_N(N - q_N) - t_P(P - q_P), \tag{5a}$$

$$\max_{p,q,I} \pi^0 \; s.t.\, N - q_N \le \overline{N} \;\text{ and } P - q_P \le \bar{P}. \tag{5b}$$

Next, a numerical model based on the analytical model is built to assess the scale of the impacts of nutrient abatement policies on two representative water utilities of different sizes. A large water utility (LWU) is over 500,000 PE based on the wastewater treatment volume, and a small water utility (SWU) is below 100,000 PE. The data used in the numerical analysis come from the Helsinki Region Environmental Services Authority (HSY) for LWU and Kymen Vesi Oy for SWU. The nutrient abatement cost functions are those of size class 2 (SWU) and size class 4 (LWU), as described in equation (1).

3 SUMMARIES OF ARTICLES

Article I. Nutrient abatement potential and abatement costs of waste water treatment plants in the Baltic Sea region

This paper assesses the current nutrient, i.e., nitrogen and phosphorus, abatement levels and loads from WWTPs across the Baltic Sea littoral countries and examines the physical potential for further reductions in the nutrient loads. Additionally, the TAC and MAC functions for both nutrients are derived based on detailed investment and operational cost data for WWTPs. These functions are used to assess the costs of reducing nutrient loads in the Baltic Sea region based on the estimated reduction potential.

The reduction potential of nutrients is large for WWTPs. The current nitrogen load from WWTPs in the Baltic Sea littoral countries is 110,000 tons per year, and the average abatement level is 61%. If all the plants abated nitrogen at least at the 70% level, which is the requirement of the EU's UWWTD, there would be 44,000 tons less nitrogen effluent per year than there is currently. At the 90% abatement level, the reduction would be 83,000 tons. For phosphorus, the current total load from WWTPs in the Baltic Sea region is 11,000 tons, and the average abatement level is 75%. The UWWTD requirement of the 80% abatement level would yield a 5700-ton reduction, and the 95% level would result in 9400 tons less phosphorus per year. The largest current loads country-wise by far originate from the WWTPs in Poland, including 66,000 tons of nitrogen and 8500 tons of phosphorus. The current average abatement levels in Poland are also low; 49% of nitrogen and 59% of phosphorus are abated. Thus, the reduction potential is huge in Poland. If the nitrogen abatement level in Polish WWTPs was 90%, the increase in the abated amount would be 53,000 tons per year, which is almost 65% of the total reduction potential in WWTPs across the Baltic Sea. At the 95% phosphorus abatement level, the reduction would be 7500 tons, matching 80% of the reduction potential of all countries.

The analyses show that the larger the WWTP is, the lower the MAC at every level of abatement. This relation applies to both nutrients and means that every kg of abated nitrogen or phosphorus at any abatement level is the cheaper the larger the WWTP is. At the 70% abatement level, the MAC of nitrogen varies from 5.5 €/kg to 9.5 €/kg between the largest and the smallest size classes, respectively. At the 90% level, the corresponding costs are 6.5 €/kg and 12 €/kg. For phosphorus, the MACs are somewhat higher than those for nitrogen, but they grow slower when compared within the size classes. The MAC at the 70% abatement level varies from 11 €/kg to 15.5 €/kg between the largest and the smallest size classes. At the 90% level, the MAC in the largest size class is only 20 cents/kg higher than that at 70%. Hence, the costs depend little on the amount, and the high phosphorus abatement levels can be justified. Moreover, phosphorus abatement is much more inexpensive in WWTPs than in agriculture.

Combining the abatement cost functions with the reduction potential analysis yields the total costs required to meet the reduction targets. Increasing the nitrogen abatement level by up to 70% in every WWTP in the Baltic Sea littoral countries would cost 310 million euros per year, and reaching the 90% level would cost 670 million euros. For phosphorus, an 80% abatement level across the region would cost 95 million euros more per year compared with the current state, and a 95% abatement level would cost 150 million euros more per year. As was the case with reduction potential, Poland also bears the lion's share of the burden concerning abatement costs. The reductions in Poland would cost 210 million euros when increasing nitrogen abatement to the 70% level, and at the 90% level, the costs would be 420 million euros. Increasing phosphorus abatement up to the 80% level would cost 79 million euros per year in Poland, and reaching the 95% level would cost 120 million euros. The share of Poland is more than 60% of the total costs of nitrogen abatement and approximately 80% of the total costs of phosphorus abatement. Overall, the costs of reducing both nitrogen and phosphorus are much lower than previously thought.

Article II. Nutrient trading between wastewater treatment plants in the Baltic Sea region

This paper examines the feasibility of nutrient trading between WWTPs in the Baltic Sea region under alternative institutional arrangements to implement the BSAP. The abatement by WWTPs, the associated costs and the trading of nutrient allowances are examined for reducing nitrogen and phosphorus loads. The model is based on a cap-and-trade approach. The cap on the total allowed maximum nutrient emissions is set for the whole Baltic Sea region. Furthermore, the sources are not allowed to increase their nutrient loads. This paper identifies trading potential and determines how abatement and the associated costs vary between the countries and size classes of WWTPs, as well as how the initial allocation scheme impacts market equilibrium and costs. The impacts of transaction costs and trading nitrogen equivalents are also studied. The results of nutrient trading are then compared with quantity constraints.

This paper demonstrates with a numerical model that a considerable share of the goals of the BSAP can be achieved by nutrient trading between WWTPs. When the allowance price reaches an equilibrium after trading begins, the solution is cost-efficient, regardless of whether the allowances are auctioned or grandfathered in the first place. In this NTS, the equilibrium prices are 6.98 €/kg and 10.78 €/kg for nitrogen when the aggregate abatement levels in the Baltic Sea region are 70% and 90%, respectively. For phosphorus abatement, the equilibrium prices are 13.95 €/kg and 16.93 €/kg under aggregate abatement levels of 80% and 95%, respectively. These prices are not high, even with high abatement levels.

When the allowances are auctioned and the cap is set at a level that corresponds to the 90% aggregate abatement of nitrogen and 95% aggregate abatement of phosphorus in the WWTPs in the Baltic Sea littoral countries, the increase in nitrogen abatement is 85,000 tons per year, and the increase in phosphorous abatement is 9600 tons per year. The corresponding cost increases per year are 600 million euros and 130 million euros for nitrogen and phosphorus abatement, respectively. Including the purchased allowances in the abatement costs yields compliance costs of 920 million euros for nitrogen trading and 170 million euros for phosphorus trading. Most of the costs fall to the WWTPs in Poland. The nitrogen abatement costs in Poland total 380 million euros, and the compliance costs total 540 million euros; additionally, the phosphorus abatement costs in Poland total 100 million euros, and the compliance costs total 130 million euros. This large disparity in the cost burden would make a comprehensive NTS in the Baltic Sea region difficult to implement. However, through the auction approach, 360 million euros would be collected. This sum could be used to provide side payments to WWTPs to even out the cost burden.

Another way to equalize the cost burden is via the grandfathering of allowances. This paper analyzes the case in which 90% of the allowances are grandfathered to the WWTPs in Poland and the rest are grandfathered to other WWTPs according to their current loads. The Polish WWTPs would be the net sellers of the allowances, and they would earn 130 million euros by trading nitrogen allowances and 10 million euros by trading phosphorus allowances. Thus, the other WWTPs would finance Polish WWTPs with 140 million euros, but the compliance costs in Poland would still total 340 million euros, which is much higher than the costs in any other country.

Under a transaction cost of 1 euro per kg for the sellers of the allowances, the Polish WWTPs would abate 1000 tons less of nitrogen per year, which is allocated to the other countries to meet the cap. For phosphorus, the WWTPs in Poland would abate 300 tons less per year. Furthermore, the WWTPs in Poland face compliance costs that are 57 million euros higher now than in the scenario without transaction costs. Hence, transaction costs may be a significant factor in an NTS in the Baltic Sea area.

Thereafter, nitrogen-equivalent trading is studied. The results describe trade equilibrium under allowance auctioning. In the Baltic Sea region, phosphorus abatement would increase by 11,000 tons, and nitrogen abatement would increase by 80,000 tons per year. The TACs in the WWTPs would total 700 million euros per year, and the compliance costs would total 1050 million euros per year.

Finally, if the overall nitrogen abatement was increased to the 90% level in WWTPs, the reduction in the load that ends up in the Baltic Sea after retention would be 35,000 tons per year. This accounts for 40% of the nitrogen reduction target of the BSAP. If phosphorus abatement was increased to the 95% level in the WWTPs, the reduction would be 3000 tons, which is 20% of the BSAP reduction target.

Article III. Impacts of alternative nutrient abatement policies on utilities supplying water and abating nutrients

The research problem addressed in this paper involves how a nutrient tax and a quantity constraint impact the behavior of water utilities and thus the prices households face. An unregulated water utility sets the water price to equalize the marginal revenue (MR) from supplying water with the marginal cost (MC) of supplying it. Moreover, the utility faces costs of abating nutrients. Tightening environmental policy, i.e., imposing a tax or quantity constraint on nutrient loads, increases the price of water as expected, but through a wastewater tariff, the price of potable water decreases. The water utility shifts the pricing to the wastewater tariff to cover the costs of an environmental policy for nutrients. Nevertheless, the total price households face increases.

Water utilities are often considered natural monopolies with high fixed costs and relatively small variable costs, which implies declining average costs (AC). When unregulated, this utility bases its pricing strategy on the AC rather than the MC to cover its costs. If the regulator has power to set the price, they may set it at a point where the AC equals the demand of water. This is called the Ramsey price; it is the price that allows the utility to break even and keeps the deadweight loss as low as possible. Often, the regulator allows the water utility to make some profit (mark-up price), even though it increases the deadweight loss in society.

The prices of water LWU and SWU as natural monopolies charge are reported, both with and without a nutrient abatement policy. MC pricing, Ramsey pricing, mark-up pricing and unregulated natural monopoly pricing are compared. Naturally, the prices increase in this order as do the deadweight losses. For example, the MC price in the case of LWU is $\hat{p}_1^e = 0.34\ €/m^3$, the Ramsey price is $\hat{p}_1^r + \frac{F_1}{W_1^r} = 0.56 + 0.31\ €/m^3$, the mark-up price is $\hat{p}_1^\pi + \frac{F_1}{W_1^\pi} = 0.63 + 0.35\ €/m^3$ and the unregulated natural monopoly price is $\hat{p}_1^m + \frac{F_1}{W_1^m} = 3.93 + 0.57\ €/m^3$. At this point, the Ramsey price and mark-up price are approximately one-third higher in SWU than in LWU.

Under a nutrient tax, the compliance cost for the water utility is higher than under a quantity constraint unless the tax is not paid back. This means that the price of water is also higher. At the baseline, the LWU charges $\hat{p}_1^r = 0.40\ €/m^3$ as a Ramsey price. A fixed fee is not reported here, as it does not provide any additional information for comparison. If the regulator imposes a nitrogen tax of 5.46 €/kg, the LWU will abate nitrogen at the 70% level and charge $\hat{p}_1^{rt} = 0.55\ €/m^3$. Under the quantity constraint of a 70% abatement level, the LWU sets a price of $\hat{p}_1^{rQ} = 0.49\ €/m^3$. As the abatement shifts toward the BAT to 90% abatement level, the corresponding prices are $\hat{p}_1^{rt} = 0.56\ €/m^3$ and $\hat{p}_1^{rQ} = 0.54\ €/m^3$. Hence, the more the abatement level increases, the less the instrument used matters. This is due to the decreasing nutrient taxes while the abatement level and costs increase. The case for phosphorus abatement is similar.

As the price of water is higher for households connected to SWU than for those connected to LWU, the nutrient abatement policy also impacts households differently. When imposing a nutrient tax on both nutrients leading to a 90% nitrogen abatement level and a 95% phosphorus abatement level, the price of water in the area served by LWU increases 30% from the baseline, while in SWU area, the price increases by 54%. Thus, the impact of the environmental policy depends on what area one lives in, i.e., what the size of the water utility that supplies potable water and treats wastewater is.

4 DISCUSSION AND CONCLUSIONS

Eutrophication causes changes in ecosystems, affects the usability of waters and influences the economy. To combat eutrophication in the Baltic Sea, nitrogen and phosphorus loads must be reduced. One of the main sources of nitrogen and phosphorus loads is WWTPs. The objective of this dissertation was to determine the physical potential of reducing nitrogen and phosphorus loads in WWTPs in the Baltic Sea littoral countries and to assess nitrogen and phosphorus abatement costs and build abatement cost functions for WWTPs. Moreover, the objective was to find a cost-effective solution for reducing nitrogen and phosphorus loads in WWTPs in the Baltic Sea littoral countries. Furthermore, how the costs are divided among the WWTPs and how the initial allocation of allowances impacts market and costs were assessed. Finally, the objective was to determine how nutrient tax and quantity constraint affect the behaviors of water utilities and thus households.

It is shown in this dissertation that there is a large reduction potential for nutrients in WWTPs in the Baltic Sea littoral countries. Additionally, the abatement costs are relatively low but unevenly distributed among the countries. The analyses show that the nutrient abatement costs are lower in WWTPs than has been reported in most of the previous studies, including those of the COWI (2007), Gren (2008a; 2008b), Hasler et al. (2012), Ahlvik et al. (2014), Wulff et al. (2014). Another finding is that phosphorus abatement costs are much lower for WWTPs than for agriculture (see Ollikainen et al. 2012).

In this dissertation, it is demonstrated that a cost-efficient solution under an NTS can even out the cost burden between WWTPs if designed properly. Initial allocation can alleviate but not entirely eliminate the uneven distribution of costs between WWTPs. Comparing the abatement costs of the NTS and the uniform quantity constraint shows that the higher the aggregate abatement level in the whole region is, the closer the abatement costs are. Moreover, taking transaction costs into account, the NTS would still yield lower abatement costs than the uniform quantity constraint approach. Although the difference in the costs between these approaches is small, there is another advantage of the NTS. The timing of the investments can be optimized under the NTS, while under the uniform quantity constraint the installations are forced to invest immediately in abatement. This feature has also been found in practice (see Downing and White 1986; Milliman and Prince 1989; EPA 2008). Overall, 40% of the BSAP nitrogen reduction target and 20% of the BSAP phosphorus reduction target could be cost-efficiently achieved with an NTS between WWTPs.

It is shown in this dissertation that environmental policies aimed at nutrient reductions may decrease the price of potable water, and the wastewater tariff will correspondingly increase. Nevertheless, the aggregate charge to households increases. Environmental policy may also unevenly treat individual water utilities and the households connected to them. Small utilities face higher costs from nutrient reduction policies than do large utilities, which in turn affects the prices households face. To distribute the burden evenly, small water utilities could be compensated to enable prices closer to those of households connected to large utilities. This could be done, for example, by nutrient trading or by side payments collected from nutrient taxes. Although water utilities charge separately for potable water and wastewater, the latter is also based on the consumption of potable water. While measuring the amount of wastewater generated in households, not to speak of its content, would be expensive, the water utilities currently charge for something they do not meter.

Reducing eutrophication in the Baltic Sea requires nutrient reductions from other sources, such as agriculture, and to intervene in the internal nutrient cycle. The means to tackle this issue include not only economic instruments but also innovations in technologies such as extracting phosphorus from wastewater for new products or using abatement process and sludge to produce energy (Ollikainen et al. 2019). The results shown in this dissertation should encourage decision makers to invest in WWTPs, as substantial nutrient reductions could be achieved without spending a large amount of money.

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